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Success Story Cutting

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Abstract

Cutting technologies are the engines behind manufacturing. Without cutting, none of our modern products would ever been put into service. Developing new materials directly needs research for process windows in cutting. Huge engineering efforts brought cutting in the position where it is today and despite all rumors trying to declare, that cutting is outdated or cutting research is finished it is still a vital field of research and prone to rapid innovations. Recent material developments challenge cutting technology. Recent material developments of cutting material as well as understanding of the cutting process enable to cope with the challenges imposed from difficult to cut materials. Research results and recent developments in machine tools show how to combine the multiple requirements from ecology, economy and quality. Machine tool, tool and process are the ingredients of success in cutting.

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Keywords: Difficult to cut materials; tool development; efficiency; machine tool

1. Introduction

The success story of cutting metals is endless. Despite of many attempts to avoid the painful path of cutting, it remains the dominant and in most cases irreplaceable process to create added value for metal parts. There is a variety of reasons for this finding. They can be roughly clustered into two categories. The first one comprises the weaknesses of the alternatives. Most of them do not replace cutting, they replace only a part of the value chain of the cutting process. The second one is more important: It is the strength of cutting, the steady improvement, the ability to adapt to new circumstances. Cutting can produce a high value part within seconds out of a bulk material. It is versatile and can produce a variety of parts with the same equipment in a flexible production. It is adaptive, producing the same final result out of bulk material, from a semi-finished good, or from the outcome of a near net shape process. It is innovative, producing more, and more precise, features. Although fluctuating with economic and occasionally technological cycles, the world market for machine tools is important and increasing, reaching 60 Billion EUR in the last few years as depicted in Fig. 1. Machine tools are predominantly metal cutting, the share of metal forming machines is about 27% in case of Germany [3].

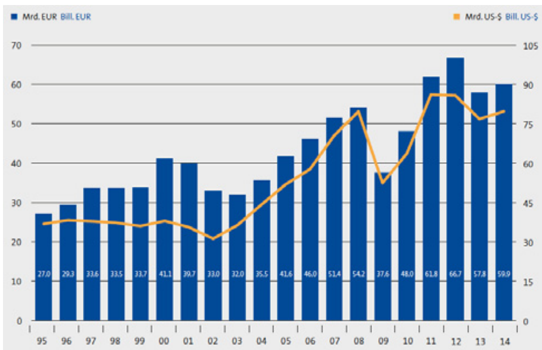

Fig. 1. World machine tool production, Source: [3]

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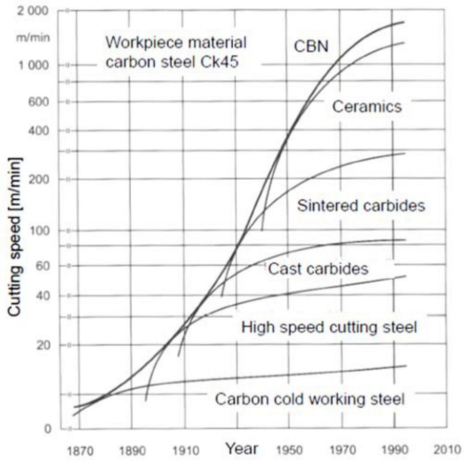

Fig. 2. Increase of cutting speed in history

It is difficult to quantify the improvement of cutting processes, ever since Taylor's masterly statement in the early 20th century [1]. One indicator is the cutting speed. Within one century, it has been increased by means of four significant technology steps by about factor 200 as shown in Fig. 2. This is an average increase of more than 5% per year, from less than 15m/min to more than 2000m/min. The difficulties of cutting processes are partly caused by the complex interaction of machine tool, material, tools and process parameters. But the same complexity explains the successful evolution. For instance, the capabilities of a new tool can easily be verified on an existing machine tool. The evolution of machine tools, materials, tools and process parameters is within limits independent, enabling and encouraging simultaneous developments by a multitude of factors. Process parameters are modified daily, tools are innovated within weeks or months; machine tools and materials within years. These overlapping innovation cycles lead to a vivid and steady evolution. The fact that the number of patent applications published in the field of machine tools (2013: 61'249) exceeds the number of those in many other fields, such as telecommunications (2013: 50'497), biotechnology (2013: 45'485) or Surface Technology/Coating (2013: 39'426) may provide some evidence [2].

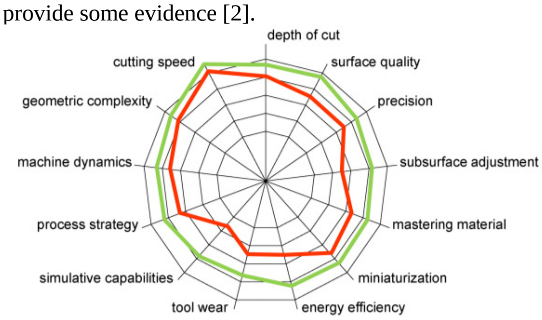

Fig. 3. Achievements and challenges in high performance cutting

Fig. 3 shows current challenges and achievements since 2002. Naturally higher material removal rate, cutting speed and feed rate was always of interest and is thus excellently developed as also Fig. 2 shows. Direct challenges for metal cutting are caused by the miniaturization, requiring smaller parts with increased functionality. Smaller parts require higher absolute precision due to the downscaling, the increased functionality causes higher complexity. Miniaturization combined with the demand for higher performance of products led to harder materials that are more difficult to machine, e. g. composites. Short innovation cycles with fast ramp-up periods ask for enhanced flexibility and production in smaller lot sizes, for mass products too [4]. Miniaturization therefore comprises the whole cycle in Fig. 3, but downscaled. Strongly questions of surface integrity, energy efficiency and simulation of cutting processes have been discussed and approached in the recent past. Finally, due to the obvious necessity of economic sustainability investments and running costs for production machines must be reduced continuously.

2. Challenge Workpiece Materials

Requirements from product development for materials with special properties to withstand the loads during their lifetimes are the most important driver for further development of cutting technology. Those materials need to be machined without damage and under the extreme cost pressure which always accompanies machining. Cutting of steel up to Ck45, which is the benchmark of all cutting is today regarded as standard cutting process. But the great progress in cutting can be seen in the drastic increase of cutting speeds for all those materials beyond Ck45. Hard to cut or hard to machine materials are generally considered as materials, which cause extreme loads, extremely high temperatures in the cutting zone and problems in chip formation and thus create excessive wear on the tool, while the class of difficult to cut materials or difficult to machine materials (DTMM) includes also materials, where cutting creates bad surfaces and introduces deterioration of the subsurface area, which are difficult to avoid. Often both aspects come together and sometimes the terms are also used synonymously. Prominent representatives of DTMM are the frequently used Ti alloys and Ni based superalloys. Refractory metals which consisted of titanium, nickel, steel, molybdenum, rhenium, tungsten, cobalt, tantalum, niobium, chromium, etc. are DTMM.

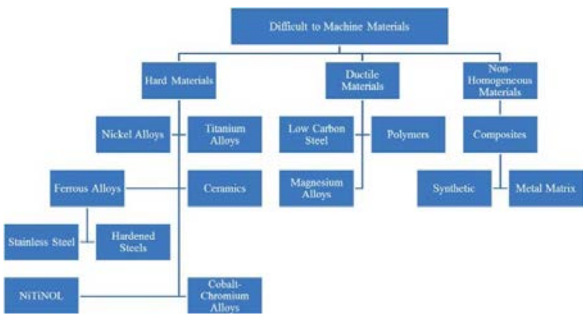

Fig. 4. Classification of difficult-to-machine materials [5].

Materials which are prone to damage of the subsurface region are structural ceramics, composites, polymers and magnesium alloys. Fig. 4 shows a classification of difficult-to-machine materials according to [5]. All of them underwent a huge increase in material removal rate and also enhancement of surface and subsurface properties due to special tool development, coolants and suitable process parameters. The adaptability of cutting is one of the secrets behind its success.

But for different materials the reasons for classifying them into DTMM is very different and is reviewed in the following.

2.1. Titanium Alloys

Due to their superior mechanical and physical properties such as: high strength to weight ratio, high yield stress, very high creep and corrosion resistivity, high toughness, high wear resistance and good biocompatibility titanium and its alloys are attractive materials in many engineering fields such as aerospace, vehicles, engines and gas turbines, nuclear, biomedical, etc.. The reasons for making Ti-alloys difficult to machine are:

- Adiabatic shear banding coupled to fluctuation of cutting force, which causes vibrations
- low elastic modulus compared to strength causing the material to elastically deflect under the tool edge radius and exert compressive forces from the flank face.
- With low elastic modulus workpiece deflections occur due to cutting forces causing chatter and vibrations
- small tool–chip contact area causing force concentration and superposition of crater wear and wear of cutting edge
- high chemical reactivity with all known tool materials,
- low thermal conductivity concentrating energy on the cutting edge
- high strain hardening due to their austenitic matrix,
- tendency to adhesion and forming BUE (build up edge),
- high dynamic shear strength

2.2. Nickel-based alloys

Very broad operational temperature makes nickel-based alloys very advantageous as construction material for aerospace, gas turbine and nuclear industries, with superalloys especially in the hot area of thermic machines. It maintains its chemical and mechanical properties at elevated temperatures over long time and is highly resistant to creep and corrosion.

The properties responsible for making nickel based alloys difficult to machine are:

- high shear strength,
- high hot strength and hardness, which is especially for superalloys the properties for which the material is designed
- high strain hardening,
- low thermal conductivity resulting in high temperature at cutting zone up to 1200°C,
- high chemical reactivity to most tool materials depending on the constituent alloying elements
- adhesion and welding tendency to the cutting tool and formation of BUE,
- presence of hard carbide particles, for example TiC, in the microstructure which encourage abrasive wear,
- small tool–chip contact area resulting in high thermal and mechanical stress close to the cutting edge,
- production of long continuous chips which hinders the machining in unmanned operations.

2.3. Stainless steels

Stainless steels, which are widely used in chemical, aerospace, automotive and food processing industries, have high strength, high fracture toughness, high fatigue and corrosion resistivity compared to plain carbon steels. Together with low thermal conductivity and high heat capacity these makes stainless steel difficult-to-machine. High cutting energy is required resulting in strong heat generation during machining. Similar to titanium and nickel alloys, in machining stainless steels the generated heat cannot effectively be transferred into the workpiece and chips due to low thermal conductivity. It is concentrated at the cutting zone and produce high cutting zone temperatures. High tool wear such as diffusion and chemical reaction between tool and workpiece materials, BUE, work hardening, poor surface quality, low productivity and high machining costs are the consequences.

2.4. Cobalt–chromium alloys

Another type of alloy which is considered extremely difficult to machine is cobalt–chromium alloys. The main material properties of these alloys are high strength, high hardness, high biocompatibility, high creep resistance and high corrosion and wear resistance superior to that of titanium based alloys. This makes Co-Cr-alloys appropriate candidates for medical implants, aero-engine, nuclear and gas turbine components. Similar to other refractory metal alloys, machinability of cobalt–chromium alloys becomes difficult due to work hardening and poor thermal conductivity of the material, resulting in low tool life and poor surface quality.

2.5. Magnesium alloys

Magnesium is the lightest structural metal, has high strength-to-weight ratio and good corrosion resistivity. Magnesium is very attractive to aerospace and automobile industries. In addition magnesium alloys are used for bio-degradable temporary implants.

Magnesium actually is good to machine, resulting in low cutting forces, good surface finish and long tool life. Problem is only its inflammability and the risk of ignition at temperatures above 450 °C. As cutting fluids for temperature control only neutral mineral oils can be used. Therefore, machining magnesium alloys is usually conducted under dry conditions resulting in low productivity.

2.6. Ceramics

Due to their high melting temperature, small thermal expansion coefficient, high hardness and wear resistivity, good strengths at high temperature, good chemical stability, ceramics become more and more interesting as it is also achieved to provide ceramic alloys with minimum ductility and thermal shock resistance as for instance for reaction bonded silicon nitride or yttrium stabilized zirconium oxides. To machine these materials the cutting tools needs to be extremely hard and wear resistant, tough and thermally stable. The appropriate tool materials are diamond (PCD) or polycrystalline boron nitride (PCBN). However in case of diamond the process temperature has to be considered carefully because of transformation to graphite at elevated temperatures. Ceramics are very sensitive to damage, so that cutting parameters must be especially adapted to surface and subsurface integrity.

2.7. Composites

Machining composites is very different to homogeneous materials due to their inhomogeneous and anisotropic nature. The cutting behaviour and chip formation of the reinforcement fibres differ widely of the behaviour of the matrix. This cutting condition can result in severe surface quality issues such as delamination, burning, fibre pull-out, uncut fibres, high surface roughness and high dimensional deviation. Only tools with very sharp cutting edges with long life time succeed in cutting without damage.

Difficult-to-machine composites are not limited to fibre reinforced plastics and cover also metal matrix composites. These new engineered materials usually have ceramic particulates such as SiC or Al_2O_3 embedded in a metal matrix of aluminium, titanium or magnesium. The presence of hard abrasive particulates harder than WC tools can cause severe tool wear, therefore adequate cutting tools with higher strength, higher abrasion resistance and higher toughness are required.

3. Cutting Tools

Development of new structural workpiece materials is directly related to the need of new materials for cutting tools, which are able to shape the workpiece with high accuracy and surface quality without unacceptable tool wear. This can only be fulfilled with high hardness and toughness at cutting temperatures. Fig. 5 shows how hardness and toughness are negatively correlated. Good thermal shock resistance is another important characteristic of suitable cutting materials.

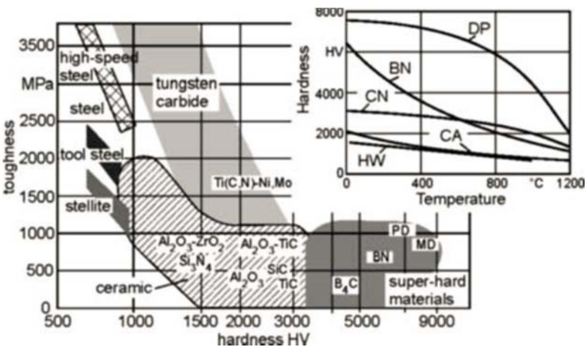

Fig. 5. Toughness and hardness of cutting materials [2].

The main problems in machining difficult-to-cut materials are very high temperature at the cutting zone, presence of abrasive carbide particles, chemical reactivity between tool and workpiece materials and high hot strength and hardness of the workpiece materials. The success of cutting depends to a great extent on the choice and availability of suitable cutting material.

Carbide tools belong to the most used tools in machining difficult-to-cut materials due to their performance to price ratio. 75%–85% of the carbide tools used in industry are coated.

Ceramic tools are considered as an attractive alternative to carbide tools in machining ferrous alloys. However they are not recommended for machining titanium alloys due to the chemical reactivity of Titanium, low toughness and poor thermal conductivity of the ceramics which causes excessive tool wear at high cutting temperatures. Ceramic tools exhibit high hardness but are very sensitive to mechanical and thermal shocks, what is also the reason that these tools are used at dry conditions.

Cubic boron nitride (CBN) and *diamond* based tools demonstrate the highest wear resistance and hot hardness among common tool materials. Unfortunately diamond tool materials are chemically reactive with titanium and steel. Conventional CBN tools are produced from CBN powder in conjunction with a metallic or ceramic binder material. Thus, the mechanical and thermal properties of CBN tools are also highly dependent on the type and quality of the binder material.

Binderless CBN tools (BCBN) are more robust because problems associated with binder materials are eliminated. BCBN tools perform much better than conventional CBN tools in machining titanium alloys and the cutting speed can be increased up to 220 m/min.

While diamond tools have the highest wear resistance and hot hardness, they are unstable at temperatures above 700 °C. Recently binderless nano-polycrystalline diamond material has been developed by Sumitomo Electric, which has the extreme hardness of monocrystalline diamonds but is isotropic in strength and wear resistivity [49].

3.1. Coatings

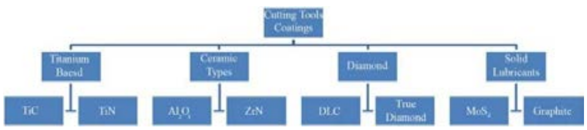

Fig. 6: Basic categories of cutting tools coatings and some examples of each category.

Different coatings have been introduced in order to improve the cutting tool performance and cope with the different requirements against wear attack on the surface and strength and toughness of the bulk material. Fig. 6 illustrates the major types of coatings used in industry. While the effect of coatings is still not fully understood in machining DTMM, generally coated tool materials perform better than uncoated carbide tools. On the contrary, Hong et al. [7] complained the effectiveness of coatings in machining titanium as Al_2O_3

reduces the heat conductivity of the cutting tool and TiC and TiN are reactive to the workpiece material.

Coatings form a barrier between the cutting tool and the workpiece materials preventing the tool material from being exposed. This reduces the diffusion rate and lowers the chemically and thermally induced tool wear such as adhesion and oxidation. Coatings can also enhance the cutting tools performance by altering the friction coefficient, increasing hot hardness, resulting in lower abrasion rate. Coatings are commonly applied by PVD- or and CVD-technology and can be mono- or multilayers. An overview of actual coatings and its properties is given in Table 1.

Table 1: List of actual typical coatings, thickness application related [8]

Coating material Coating structure	Coating hardness HIT (GPa)	Residual Stresses	Maximum application temp. (°C)	Suitable substrates	Coating colour
TiN Monolayer	30 +/-3	-2 +/-1	600	HSS, PM-HSS, Carbide	golden yellow
AlCrN-based Monolayer	36 +/-3	-3 +/-1	1,100	HSS, PM-HSS, Carbide	light grey
AlCrN-based Multilayer	34 +/-3	-3 +/-1	>1,100	Carbide	blue grey
AlCrN-based Multilayer	38 +/-3	-3 +/-1	>1,100	HSS, PM-HSS, Carbide	light grey
AlCrN-based Multilayer	40 +/-3	-4 +/-1	>1,100	HSS, PM-HSS, Carbide	light grey
TiCN Multilayer	37 +/-3	-3 +/-1	400	HSS, PM-HSS, Carbide	blue grey
Diamond Monolayer	80-100	–	600	Carbide	grey
Carbon-based Monolayer	50 +/-5	-5	500	HSS, PM-HSS, Carbide	black
AlTiN-based Monolayer	35 +/-3	-3 +/-1	1000	HSS, PM-HSS, Carbide	grey
AlTiN-based Nanolayer	35 +/-3	-4 +/-1	1000	Carbide	aubergine grey

3.2. Cutting edge radius

Besides conventional macroscopic cutting tool design parameters as rake angle, clearance angle, chip breaker geometry in the last years the cutting edge radius and the surface conditioning of cutting tools is revealed by Denkena et al. [38] to be important. A cutting edge radius adjusted to the processing tasks and the workpiece material reduces tool wear and thus extends the tool life time considerably. Wyen [9] proposed for the milling of titanium Ti6Al4V an optimal cutting edge radius of 15µm. As the cutting edge radius controls the direction of the ploughing force this optimum radius is found to orient the ploughing force in the bisection of the cutting wedge. For drilling carbon fibre reinforced polymers (CFRP), Henerichs [10] showed that the cutting tool should be as sharp as possible to reach acceptable machined workpiece quality with low forces. Due to the abrasiveness of CFRP with high fibre content, diamond tools are increasingly used for high volume cutting operations. The hard and sliding-wear-resistant diamond coating protects the comparatively soft cutting edge from rapidly getting worn and rounded and directs the wear to the flank face. But the diamond coating increases the cutting edge radius from ideally 4µm after grinding up to 10 - 16µm after coating. In consequence Henerichs et al. [11] and Wang et al. [12] show that diamond coated carbide tools exhibit poor bore exit quality until the coating smoothens within the first bores (run-in period): The quantity of poor bores depends on tool geometry, coating and CFRP material. Fig. 7 shows the run in of two different diamond coated tool geometries A and B, starting from fairly poor but still post processable and thus acceptable appearance of the bore exits to excellent bores after 150 and 250 bores respectively. Afterwards the bore exits are free from uncut fibres or delamination at least until the 1000th bore, when the test was stopped. In the lower part of Fig. 7 the self-sharpening of two CFRP-drill geometries is shown. After 600 bores the cutting edge radius is reduced from initially 14µm down to 2.6µm for geometry A respectively from 17µm down to 3.4µm for geometry B. This cutting edge radius can be kept up again to end of test at bore 1000. Voss et al. [13] showed also a possibility to pre-sharpen the cutting edges of drills by means of a 10 ps pulsed laser, thus generating cutting edges, which from the first bore onwards yield excellent results. Thus the success of the cutting tool can be shaped by taking into account the tool geometry and not only the geometry in the as fabricated state but in the worn state to extend the life time of the tool and the economy of cutting this DTMM.

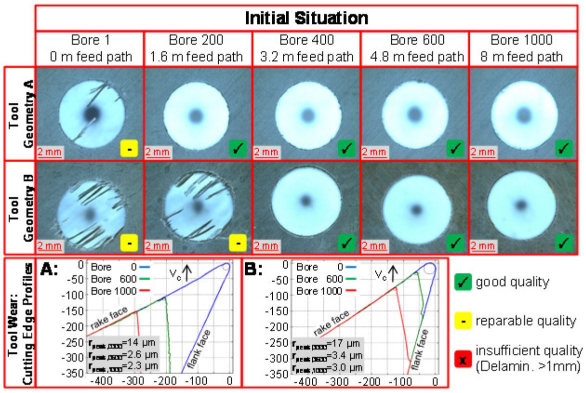

Fig. 7. Initial bore exit quality of diamond coated tools and wear profiles [13].

3.3. Drills and endmills for hard materials

In the 1980s full carbide tools for milling and drilling just appeared in the manufacturing industry, whereas before only inserts of carbides were available, while drills were made of high speed steels. Advances in sintering technology made this step possible. Ceramics were at that times only used as inserts. About 2010 first full ceramic milling tools appeared in industry shifting the limits of current cutting technology towards DTMM, so far not economically machinable. Material development, ceramics with high fracture toughness, were the enabling technology for this step. Since 2015 now drills and end mills from PCD are available for use in industry. Materials like ceramics, which formerly were only possible to machine by grinding, are now possible to machine with geometrically defined cutting edges, i.e. milling and drilling, and thus drastically change the landscape of cutting technology. Recent developments of ultrashort-pulsed lasers are here the enabling technology, which make it feasible to shape cutting wedges with sufficient flexibility in geometry in ultrahard materials like diamond and CBN. The shortness of the laser pulses enables material removal without phase change for instance from diamond to graphite and achieves good preciseness. Warhanek et al. [14] report on the tangential laser machining and geometry optimization of polycrystalline diamond tools for the end milling of sintered Zirconia (ZrO_2, TZP-A). Three different tool geometries and a variation in rake and clearance angles are manufactured to investigate the effects on processing forces and tool lifetime in practical dry end milling application. The results are applied to the design of an end mill shown in Fig. 8 achieving a specific material removal rate of 1.2mm³/(mms) and over a specific tool life a material removal of 8000 mm³/mm.

Fig. 8. PCD torus milling tool (diameter 1.8mm) with optimized geometry: both rake and clearance angle = 5°, angle of twist =45°, torus radius = 0.1mm, with 13 helical cutting edges.

Fig. 9. ZrO_2 drilling tests with a laser-processed 1.8 mm PCD tool.

A similar study is done by Warhanek et al. [15] for PCD drilling tools. The generated chips of dry drilling test in Zirconium dioxide (TZP-A) with these laser processed PCD tools demonstrates Fig. 9. The PCD tools produce needle-like chips up to 700 µm in length, which is in the length range of the primary cutting edges. These chips indicate a material removal mainly in the ductile regime. This chipping mode allows for high precision machining with superior surface quality and minimum damage caused by fractures during the cutting process.

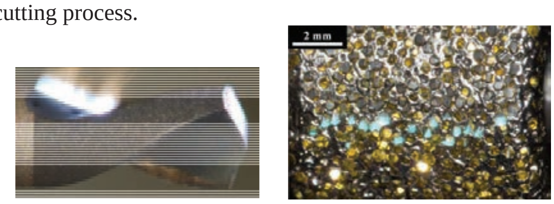

Fig. 10. Laser-manufacturing of the PCD drill (left), Laser-manufacturing of a diamond dressing tool right.

The ultrashort pulsed laser processing, shown in Fig. 10 is the enabling technology for cutting, making manufacturing tools, which are impossible to manufacture otherwise. The concept of tangential processing of ultrahard materials can also be adopted to prepare dressing tools by laser touch dressing, where the cutting edges of the grains are levelled to a smooth horizon. And also grinding wheels with remarkable profile sharpness and good wear resistivity are possible to generate, as the grains at edges are not removed by the collision with a mechanical profiling tool, but shaped to the desired geometry as it is shown in Fig. 11

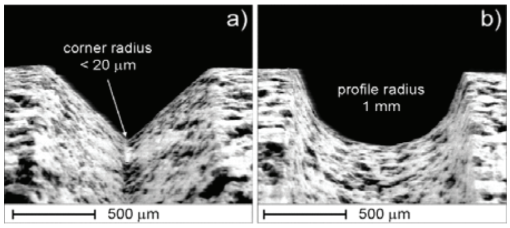

Fig. 11. Grinding wheel profiled tangentially by pulsed laser beam, grain size 46 µm.

The progress of tool manufacturing with ultrashort pulsed lasers is possible due to the following advantages:

- • The hardness of the tool material has no influence on the shaping process
- • Slender and tiny tools become possible and reach high accuracy, because the laser does not exert forces
- • As the tool "laser" is not subject to wear, the machining result is more robust and precise.
- • The small focus radius and minimum-inertial effects of the beam delivery is the basis for the unique flexibility.
- The laser is capable to shape abrasive grains in grinding wheels without breaking out or grain damage.

Fig. 12 shows the structuring of grinding wheels to enhance cooling, reduce friction and thus grinding burn. Even flank faces with positive clearance angles and more positive rake angles can be made with laser treatment, which enlarges the range of applicability of cutting with geometrically non defined cutting edges [39].

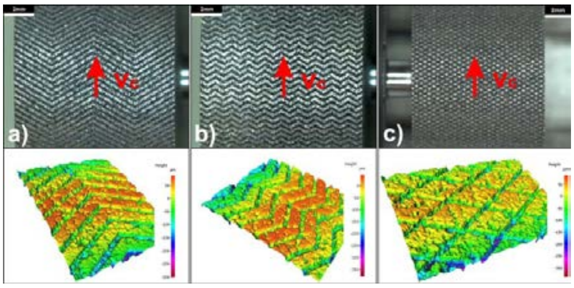

Fig. 12. Microstructures on surfaces of CBN grinding wheels.

4. Coolant, Lubrication

From standpoint of ecologic footprint coolants are regarded as harmful. Nevertheless as pointed out by Brinksmeier et al. [48] the suitable application of suitable coolants can improve cutting, cutting results and reduce tool wear drastically and is part of the success story of cutting.

4.1. Flood Cooling

In most conventional cutting processes, flood cooling is applied with either oil-in-water emulsions or neat oils [16]. Whereas in the early days of cutting fluids, one product has been used for the whole range of cutting processes, today there are many specialized products available. The main functions of a cutting fluid are to lubricate and cool the process. Additional functions are to prevent the machine tool and the workpiece from corrosion, flush the chips and cool the machine tool and the workpiece to reduce distortions. In order to comply with all the requirements, modern cutting fluids contain many different additives.

4.2. Supply Units

Cutting fluids are supplied at an ever increasing pressure. Supply units with a pressure of 300 bar and more are commercially available. The corresponding tools were developed as well. Higher pressures lead to a better cooling of the chip in statu nascendi, which leads in turn to a more brittle behavior and ultimately shorter chips due to the higher bending stress. However the shorter contact length with the tool can lead to increased wear [17]. Modern supply units feature frequency controlled pump drives which allow for an optimal operating point at different pressures and flow rates.

4.3. Nozzle Design

A proper nozzle design and adjustment has proven critical in reducing the needed cutting fluid flow rate, improving the surface quality or reducing the cycle time. In turning, state of the art tool holders feature small nozzles near the cutting edge to limit wasted cutting fluid. In milling, the contact conditions are in general varying over a large range and an optimized external nozzle is hard to design. Whenever possible, cutting fluid is therefore brought through the spindle to the cutting edge of the milling tool. In cylindrical grinding it is possible to design highly optimized nozzle systems which can often lead to a massive reduction in cutting fluid flow rate over conventional setups with segmented hoses [16].

4.4. Minimum Quantity Lubrication

Minimum quantity lubrication (MQL) is used when purchasing and disposal of the cutting fluid are not economically or ecologically feasible. A small amount of cutting fluid is mixed with a stream of gas and supplied to the cutting zone. MQL leads to a significant reduction of the cutting temperatures over dry machining [17]. Disposal of the cutting fluid is not necessary, because it sticks to the workpiece and chips or evaporates.

4.5. Cryogenic Cooling

Cryogenic cooling usually involves the usage of liquid carbon dioxide or nitrogen. One example of its application are nickel-based superalloys. They tend to have higher strengths than the tool material at high temperatures and are very tough. With conventional cooling, they lead to long chips and high wear [18]. When cryogenically cooled, these materials get brittle and chip breaking is facilitated. Wear is reduced by slowing down diffusion processes. Cryogenic cooling units with carbon dioxide, often combined with MQL, are available on the market. Units with liquid nitrogen are still at an experimental stage.

5. Machine Tools and Accuracy

The machine tool is the enabler for all cutting processes. The development up to today's modern machine tools has a decisive influence on the success of cutting. As stated above, strongpoints of cutting are the superior surface quality and the superior accuracy. Enhanced cutting tools and cutting tool materials lead to drastically increased cutting speeds, feed rates and material removal rates. Increased power of the spindle as well as the drives are the consequences and need to be born by the machine structure. For the cutting process as for all machining processes the relative motion between tool and workpiece defines the resulting geometry of the machined surface. In the case of cutting, which is a position controlled process, the structure of the machine provides the dynamic and static constraints on the displacements between workpiece and the tool.

While offering positioning uncertainties in the range of dedicated coordinate measuring machines working under well controlled environments solely under probing forces and static loads due to workpiece weight, for cutting machines process forces and significant thermal loads given by the main spindle are to be coped with. All components in the kinematic / metrological / mechatronic chain between tool and workpiece can be seen as contributors to machining uncertainty and therefore have to be regarded. The axis measuring systems providing accuracy, resolution and repeatability are the link between the NC control and the mechanics of the machine, strongly influenced by their mounting location. Based on the set-point value generation the drives apply the commanded forces on the mechanical structure. The properties of the structural components responsible for the force transmission in single direction of the prescribed motion but also for controlling the five other degrees of freedom reduce the final accuracy. Apart from this component level approach being mirrored by the investigation of component errors, the deviations such as structural deflections are strongly influenced by design specifications, choice of axis configuration or machine topology on concept level.

A subset of influences, responsible for up to 75% of the geometric deviations at the workpiece is given by thermal influences illustrated in Fig. 13 from [20]. All internal but also external heat sources may contribute to the resulting errors at the tool centre point (TCP).

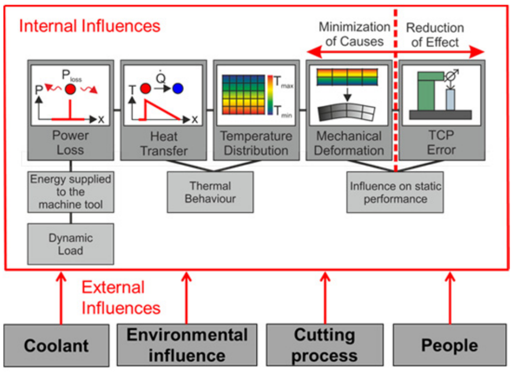

Fig. 13. Chain of causes for thermal TCP-errors [20].

Following a CIRP keynote [22] given by Schwenke, the measurement and compensation of geometric errors of machine tools can be summarised no better than stated there in the following way: “To perform compensation of geometric errors requires an understanding of the sources and the effects of geometry errors in machines and calibration procedures”.

For the compensation of thermal effects the time dependent variation of the deviations depending on the actual thermal state of the machine requires appropriate models to represent the displacements at the TCP which cannot be governed based on the measurement system values.

The underlying principle of determinism can also be found by Bringmann [23] and [24], concluding, that a main factor on the achievable calibration quality is determined by the machine performance itself. Errors that are difficult to be compensated, such as cyclic deviations with relatively short wavelength are deteriorating the quality of calibrations. Besides these effects such errors have also of course a direct influence on machined parts (“You have to pay for bad axes twice!”[24])

On component level it can be concluded to estimate repeatability as limit for any compensation of machine errors, which marks the main paradigm shift in design for compensation

Taking into account the variety of influences arising on component and concept level, alternative solutions seem to offer significant improvements. As example for an alternative concept is the planar guided Präzoplan milling machine (Fig. 14) [25]. On concept level, a granite guiding surface is used as mechanical base for an XY-movement of the workpiece table. By doing so, there is only one mechanical interface in the vertical direction which leads to increased stiffness and accuracy. Additionally, the position feed-back in X-Y-direction is realised by using a cross-grid being located on the underside of the workpiece table. The reader head in the granite ground plate which is aligned with the spindle axis offers measurement of the actual X- and Y-positions with minimised Abbe error.

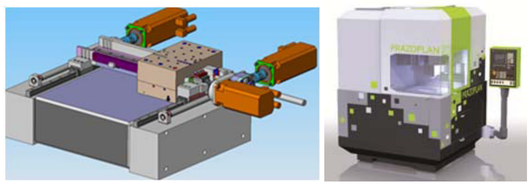

Fig. 14. Präzoplan, planar guided milling machine left: design principle, right: machine prototype built at IWF [25].

For the vertical planar bearing a large number of aerostatic guideway nozzle modules (Fig. 15) are used incorporating six triangular channels. For rigidity, these nozzles [26] are directly integrated in to the workpiece table.

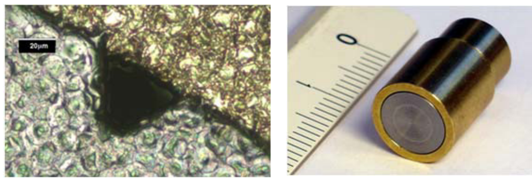

Fig. 15. Triangular Cross section of a single channel [26].

A significant aspect is given by the availability of metrological devices which can cope with the ever increasing requirements and varieties of aspects to be assessed. While, in the past, the static, geometric behaviour of mainly linear axis was in the focus, more and more the dynamic deviations of the axes in general, also the deviations of rotary axes gain importance. This is due to increased productivity asking for higher accelerations and increased appearance and use of five axis manufacturing.

The R-Test (Fig. 16) [27] is such a measurement system which can be applied for the variety of recent metrological tasks such as determination of location errors of rotary axes or evaluation of systematic cross-talk parameters which can then be used for either adjustment of kinematic parameters or application of cross-talk compensation in the NC.

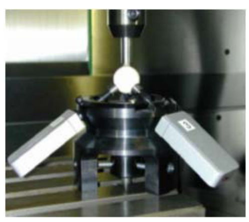

Fig. 16. R-Test measurement setup [27].

Compensation of errors needs models that can be fast evaluated. For thermal compensation different types of models are given in [20]. Recently, the use of grey-box models shows an efficient way to represent the thermal deviations on machine tools. In contrast to large models based on FE-representation of the structure, the PT1-based representation of the deviations using grey-box models offers the base for implementation in actual NC-implementation with still has limited numerical power [28]. Fig. 17 shows as example the accordance of location error values X0C for a C-axis load cycle for a 5-axis milling machines. The thermal displacements rom an arbitrarily generated test cycle is compared with simulated values, based on parameters, identified in a different test cycle. Since the stability of the simulation procedure is thus proven, this simplified model can be utilized for compensation of thermal errors.

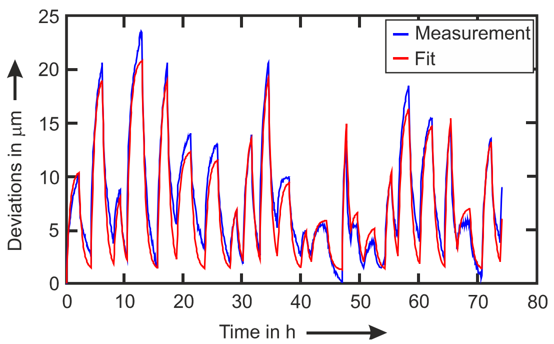

Fig. 17. Application of a grey-box-model: comparison of measured and calculated X0C-values [28].

Thermal compensation and compensation of kinematic errors are stationary tools to enhance the quality of a machine tool. In cutting quality of parts and productivity are negatively correlated to each other, which is mainly due to limited dynamic stiffness of the structural parts of the machine tool. Thus only dynamic compensation seems to be the solution to overcome this situation. Control systems today decouple the axes artificially. Taking into account the machine tool topology the interference between different axes are revealed and can be classified in cross- and intalk and coupling force effects.

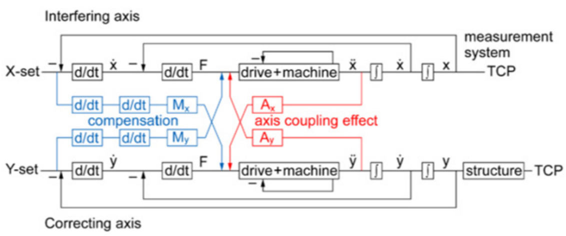

Fig. 18. A control scheme for compensation of axes coupling effects [21]

While cross- and intalk have no effect on the control system and thus can only be overcome by a model based approach, coupling force effects can be detected by measuring systems but nevertheless cannot be counteracted due to the dynamic property. All three can be compensated by model based controls, which are capable to predict already from the NC-program the deviations on TCP due to accelerations and drive forces. Fig. 18 shows as example a control scheme for the coupling force compensation according to Wegener et al. [21].

6. Resource Efficiency

Today one of the most important requirements and thus drivers for manufacturing process development are costs. Especially the choice of cutting for part manufacturing is made because of costs, which shows, that cutting in infinite cases has proven its cost worthiness, which is part of the success story. In future Energy and material efficiency of manufacturing but also of the manufactured parts gain importance and for the continuation of the success of cutting need to be taken into account. In many cases they are already promising fields to reduce the costs both of product manufacturing and use as well as the environmental burden of products. ISO 50001 [29] defines energy efficiency as “ratio of other quantitative relationship between an output or performance, service, good or energy, and an input of energy” [30]. Improving energy efficiency means simply stated to achieve more output with less energy input. Earlier studies on the topic [31] revealed that the actual cutting energy, i. e. the energy supplied to spindle and drives in case of a milling machine, represents less than 50% of the energy supplied to a machine tool. An important share of energy is supplied to pumps for cooling and lubrication, which is necessary for process stability and therefore in the first place a conditio sine qua non.

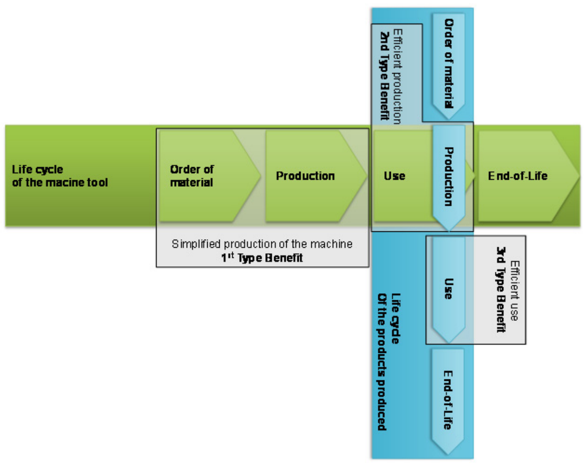

Fig. 19: Three types of benefit of ecodesign in production, according to [32].

Another aspect is the consideration of resource efficiency in a broader sense. This live cycle oriented view also takes into account the energy and emissions embodied in the used material. A model for the intersecting life cycles of machine tools and products has been developed by [32]. The model distinguishes between three types of benefits regarding resource efficiency of machine tools and their products:

- 1st type benefit: Efficiency during machine tool production.
- 2nd type benefit: Efficiency during machine tool use.
- 3rd type benefit: Efficiency during use of products, which have been produced on the machine tool.

Especially the 2nd and 3rd type benefits have proven to have a high leverage on resource efficiency, as underpinned by the European Commission by issuing the energy-related product directive (ErP) [33].

The machine tools are complex mechatronic system, which are assembled of a number of components, such as electric drives, pumps and fans. The ISO 14955 series (under development) deals with the environmental evaluation of machine tools. Two open fields of research emerge from the existing part of ISO 14955:

1. How to quantify the energy efficiency of machine tools taking into account the complexity and variability in design.
2. How to take into account the factory environment into the energy balance.

Schudeleit et al. [34] assessed different methods for evaluation of energy efficiency of machine tools using a multi-criteria decision making technique and concluding that components benchmarks are the most feasible approach for assessing the energy efficiency of a machine tool. A metric referred to as total energy efficiency index (TEEI) has been developed by [35] satisfying both, the study results and the sustainability strategies popularized by [36]. The metric takes into account the component conversion efficiency as well as its need-based utilization and referring it to the best available technology. A case study on a turning machine led to a TEEI of about 45%.

The machine tool consumes electricity as well as compressed air in order to perform a manufacturing task. Electricity is converted into heat, which needs to be removed from the machine tool as well as from the factory. The heat removal is task of the air conditioning system as well as the water cooling system, which are both part of the technical building service (TBS). The associated energy consumption of the TBS for heat removal is not quantified by current studies, e.g. [37], [38], [39]. A case study on a grinding machine [40] revealed an up to 84% increase in energy consumption due to taking into account the TBS.

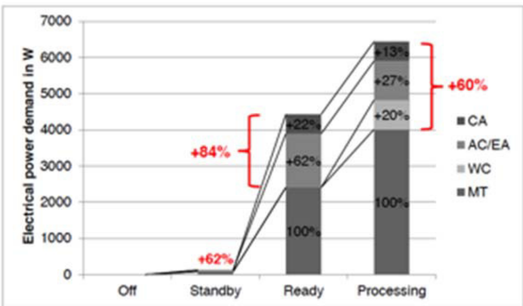

Fig. 20: Increase of energy consumption taking into account of TBS (CA compressed air, AC/EA air conditioning/exhaust air, WC water cooling, MT machine tool) according to [39].

The high embodied energy of materials and the systematic material loss due to the cutting process oblige to focus on material efficiency. Raw material is extracted and manufactured to blanks. The energy used for this procedure is referred to as embodied energy. Ashby [40] quantifies the approximate embodied energies of virgin aluminum and steel blanks by 210 MJ/kg and 27 MJ/kg. Cutting subtracts material from the blanks in order to produce a desired shape. The difference between product weight and blank weight is the produced amount of waste.

According to a literature study [39], buy-to-fly ratios between 12:1 to 25:1 can be obtained for aircraft parts. Assuming a more optimistic buy-to-fly ratio of 10:1 means for a 10 kg piece and the above stated embodied energy values a waste energy of 1890 MJ and 243 MJ for aluminum and steel, respectively.

This exemplary calculation shifts the focus towards near net shape and additive instead of subtractive manufacturing processes, providing significantly higher material efficiency. However, cutting processes cannot be abandoned when discussing surface finishing, which is often responsible for the 3rd type benefit and which is also in general the time and energy consuming part of manufacturing. This requires consideration of the whole process chain and a comparison of processes not only with the energy used for change of shape but also energy, which is required per area of surface finish as stated in [42].

Weber & Züst [31] show how hard fine milling and subsequent hard fine grinding can lead to a high surface finishing quality in selected cases. For the case of camshafts this reduces friction and leads to significant energy savings during the use phase of the product class of 3rd type benefits. Due to the high 3rd type benefits, the focus in metal cutting will shift from high removal rates to high finishing quality. This trend is supported by the evolution in cast technology, metal forming and additive manufacturing processes, reducing the added value of cutting processes to geometrical precision and surface quality.

7. UP- und Micromachining

Ultra precision machining has a long tradition and started before 1920. No other manufacturing process besides cutting is able to span the large range from material removal of litres per minute down to accuracies in the range of 10 nm. The maximum possible precision went always along with the state of the art of machine tool components as bearings, guidings, spindles, measuring systems and controls. The achievable machining accuracy from the early 20th century until today is described by Zhang [43] and summarized in Fig. 21. According to Brinksmeier [44], Evans [45] and Marsilius [46] milestones in the evolution of diamond machining which to an extend laid the basis for ultraprecision manufacturing were driven by applications as optics and optical surfaces, copying devices, computer technology and electronics, laser technology, defence and aerospace. Main steps in the development were spindles with runout of less than 50 nm, which were already available in the late sixties, high resolution measuring scales and feedback loops as well as ultrasharp cutting edges in monocrystalline diamonds.

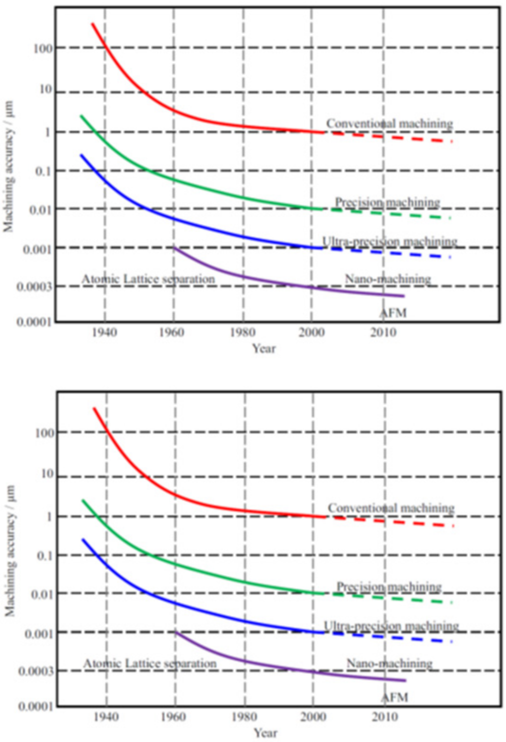

Fig. 21. Achievable machining accuracy [43]

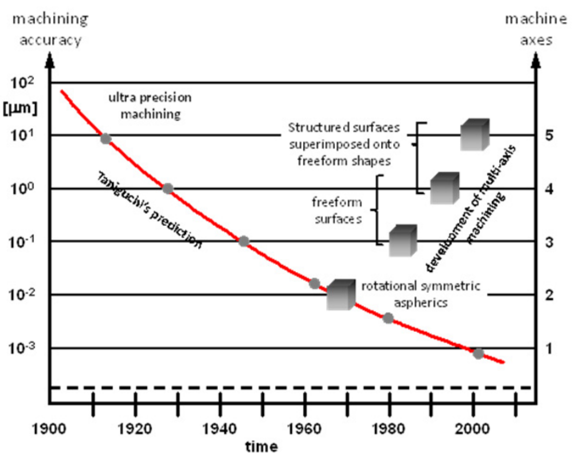

Fig. 22. Development of ultraprecision machines, enabler for ultraprecision manufacturing [47].

For the machining of more complex workpieces multi-axis machine tools are needed. Riemer [47] describes the advances of UP-machining systems towards higher accuracy and complexity in Fig. 22, which shows the development of positioning accuracy according to Taniguchi in 2 dimensions and the achievements in more than 2 axes, revealing the loss of positioning accuracy with increasing number of axes.

Equally important is the loss of productivity connected with increasing accuracy. The today possible feed velocities in UP machining for the fly cutting and planing is given as follows:

- Fly cutting process: $v_f = 5 \ldots 500$ mm/min
- Planing process: $v_f = 900 \ldots 25'000$ mm/min

The feed velocity is certainly a very important key factor for productivity. High quality with high productivity can as stated above achieved with extremely stiff machines and elaborated compensation processes. But in addition economy of UP machining can be enhanced only by strongly reproducible processes and further by the automation of the todays mainly manually machine operation.

Some important features regarding machine design can be summarized based on the list provided by Riemer [47]. The developments make today's ultra-precision machining systems more productive, more precise, and lower in price:

- Thermal and mechanical stability as well as good damping properties through machine bases made from polymer concrete or natural granite.
- Precise positioning measuring and calibration techniques
- Exploitation of compensation strategies against thermal and dynamic errors
- Linear axes equipped with hydrostatic oil bearings with oil gaps of less than 5 µm for improved damping and wear free smooth motions at highest geometrical accuracy
- Ultra precise roller guidings with large number of individual rollers.
- High-resolution linear scales with resolution of 1 nm and below replacing laser interferometers for nanometric axis position and improved geometrical accuracy.
- High feed rates direct contact to the process and excellent dynamic stiffness obtained by linear motors.
- Environmental control by air-conditioning of machine housings and customized systems for enhanced vibration isolation.
- High load capacity and stiff aerostatic spindles guaranteeing high-speed applications.
- Grinding and polishing of diamond tools with well-defined geometry and sub-micron cutting edge waviness.
- Advanced drive and feedback devices to improve work piece accuracy.
- On machine work piece measurement and error compensation systems to access residual work piece errors.
- Multi-axis machines, fast tool servo and slow slide servo turning for freeform machining.
- Dedicated software for free form machining and in situ metrology.
- Computer aided clamping of parts
- In situ tool generation of micro tools to reduce runout

Success factor and enabler for the UP- as well as micro machining has always been the development of suitable machines and components. But the development of micro tools, especially the possibility to produce micro tools as discussed above has had a strong impact on the progress in micro machining.

8. Conclusion

Continuous success of cutting is due to its uniqueness in capability to create high accuracy and good surface quality and its flexibility. Only additive methods are superior to cutting in terms of flexibility, but are incapable to generate good surfaces and as accurate parts as cutting. Drawback of cutting is its slowness in comparison to forming processes. This is the backside of the medal of high flexibility. As clear difference to forming the description of cutting processes is local, which means that only the vicinity of the cutting edge needs to be discussed for enhancing the process, while in forming the description always needs to be global, the whole part needs to be simulated for enhancing the process. For cutting, however, the whole geometry is defined by the path specified by the machine tool control. Cutting succeeds in large material removal as for aerospace industry as well as for ultraprecision parts, finishing, specular surface milling and turning. Cutting spans from all manufacturing processes the largest range of shape change rates, the largest range of accuracy and also the largest range of surface qualities. The competition as well as the complementarity between cutting with geometrical defined cutting edges and non-defined edges keeps cutting an ever vital research field. While cutting typically is associated with geometric control of the tool movement, also force controlled processes as polishing fine finishing, honing etc. are cutting processes and capable to limit the surface roughness to Nanometer level. While grinding has its strengths in the manufacturing of extreme fine surfaces, extreme accuracies but also to materials of extreme hardness. Ingredients for the success of cutting are cutting tools, cutting fluids, cutting strategies and the machine tools.

As shown in the paper the utilization of new materials for cutting tools and the development of non-cutting technologies for manufacturing of cutting tools is a game changer between grinding and cutting with geometrically defined cutting edges. Laser manufacturing offers nearly infinite design flexibility in ultra-hard materials like CBN and poly- and monocrystalline diamonds. Now tool geometries, cutting edges and chip brakers which are clearly unachievable by grinding processes can be manufactured. With those tools brittle-hard materials like ceramics, glass, carbides can be shaped by tools with geometrically defined cutting edges. But this technology also opens the field to manufacturing of micro tools down to 20 µm, it opens the field for manufacturing and cutting edge preparation of tools suitable for sensitive materials like CFRP and thus gives a huge impulse towards future success of cutting.

It is essential to keep in mind, that cutting machines are the prerequisite for all cutting processes and especially enable and limit cutting technology. Whether it is the stability against chatter in high material removal rates, kinematic accuracy and thermal stability, the machine governs the process. Especially the basic negative correlation between accuracy and productivity needs to be overcome. The first approach always needs to be design and construction of the machine, which needs to be done according to the requirements of advanced cutting processes. But compensation to enhance good designed machine tools grows into the focus of machine building and is capable to further push the limits of cutting processes.

Not only the quality of cutting plays a role, but the requirements management of cutting processes and thus machine tools contains total cost of ownership and resource efficiency. Energy efficiency and quality of products meet to reduce thermal errors. Saving energy requirement mainly leads to media supply especially coolant supply. Today coolant is after an era of disregard again seen as a liquid tool and its value is clearly esteemed. As stated by Brinksmeier et al. [48] coolants have a huge cantilever in reducing friction and cutting forces already by their chemistry but also by their physical properties. It is today not only grinding, which resists to dry machining, but a trend change towards suitable process cooling instead of avoidance of cooling also in other cutting processes can be observed.

As cutting technology is developed to a good state of maturity and thus the evolution goes in the direction of saturation, progress often requires exploiting small and tricky advantages. Besides enduring experiments, simulation technology develops fast, because it promises the only possibility to systematically explore the parameter field of cutting and optimize the processes. Today still somehow awkward in describing the observed phenomena, but the learning curve is tremendous, which nourishes the expectation of becoming the optimization tool of the future as it has taken place in forming.

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